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Research article

A nine-year study on the benefits and risks of soil and water conservation practices in the humid highlands of Ethiopia: The Debre Mawi watershed

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A R T I C L E I N F O

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A B S T R A C T

A nine-year (2010–2018) field study in the Debre Mawi watershed was conducted to understand the effect of governmentally-imposed and farmer-initiated conservation practices. The watershed is in the sub-humid Ethiopian Highlands which experience high and increasing erosion rates despite years of conservation efforts. Consequently, reservoirs are filling up with sediment and soil degradation is enhanced, calling for the evaluation of conservation practices currently in use. The few past long-term experimental studies on structural practices are inconclusive. In addition, only anecdotal information is available for streamflow and sediment loss. Precipitation, stream discharge, and suspended sediment concentrations were recorded manually in the Debre Mawi watershed during the nine-year period. Groundwater depth and total saturated area measurements were taken for selected periods. From 2012 to 2014, government-mandated conservation practices were constructed, which consisted of 50-cm-deep infiltration furrows with bunds downslope. These furrows were filled in with sediment by 2018. At the same time, the acreage of eucalyptus trees planted by farmers on the most vulnerable lands tripled to 5% of the total area with most trees fully grown in 2018. Runoff coefficients and sediment concentrations decreased steadily throughout the nine years. In the saturated bottomlands, the observations suggested that government-sponsored infiltration furrows in the saturated bottomlands were ineffective and may concentrate flows and enhance gully erosion, while eucalyptus trees appear effective. The results of this observational study point to both the potential benefits of conservation practices in this sub-humid tropical highland region and to emerging long-term risks. If structural conservation is to be pursued in watersheds like Debre Mawi, due attention must be given to the safe removal of excess water from the valley bottoms. The vegetative farmer-initiated practice of planting eucalyptus trees effectively reduced streamflow and erosion, but at the same time, might dry up wells during the dry monsoon phase which should be investigated further.

1. Introduction

Land degradation and resulting soil erosion are critical impairments in Africa, specifically in the Ethiopian Highlands (Shiferaw and Holden, 1999) where the magnitude of soil loss varies (Hurni, 1993; SCRP, 2000). In watersheds without gullies, soil loss is usually below 20 Mg ha^{-1} a^{-1} (or tons/ha/year) (Moges et al., 2016), whereas watersheds with active gullies experience greater than 25 Mg ha^{-1} a^{-1} and up to 540 Mg ha^{-1} a^{-1} of soil loss (Tebebu et al., 2010). A national scale study (FAO, 1986) estimated that annual average soil loss in Ethiopia is about

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2 Tg (billion ton). In the Upper Blue Nile Basin, land degradation is a critical problem for crop production, siltation of reservoirs, and hydropower production (Assefa et al., 2015; Worqlul et al., 2017; Mhiret et al., 2018). Such land degradation, particularly in the Ethiopian Highlands of the Upper Blue Nile Basin, has been a problem since at least the 1960s, following the replacement of forest lands with cultivated lands (Mitiku et al., 2006; Tato and Hurni, 1992; Constable and Belshaw, 1986). Lake Tana, the largest lake in Ethiopia and the source of the Blue Nile, has been greatly affected by this land degradation and associated soil loss (Zimale et al., 2018). Major Cheesman, who surveyed the lake in the early 1930s, noted that the lake had a sandy bottom near river outlets at a time when Ethiopia was less populated and shifting cultivation could be practiced (Cheesman, 1935). Currently, there are large mudflats around the same outlets (Abate et al., 2015).

In response to land degradation and its effects on reducing food safety, watershed management interventions have been implemented widely for centuries all over the world. For example, Native American farming cultures in the southwestern United States used indigenous soil and water conservation practices for at least 1500 years (Pretty and Shah, 1997). Conservation programs implemented in the early 1900s in the US western plains ignored the Native American indigenous practices in favor of technocratic approaches by governmental agencies in the 1930s during the droughts that were responsible for the dust storms (Warrick, 1980). In Africa, technocratic approaches were implemented as well by the colonial regimes initially and then after independence by the governments in cooperation with foreign consultants (Pretty and Shah, 1997). In Ethiopia, interventions consisted of both traditional and governmental sponsored technocratic soil and water conservation practices (SWCPs). Traditional practices in the humid Highlands consist of shallow off-contour furrows that are plowed in each year to carry off excess rainfall and, more recently, planting trees on erosive and saturated lands. Imported technocratic practices are soil bunds, stone bunds, and Fanyaa Juu terraces (Mitiku et al., 2006). These landscape modifications are aimed at both conserving water by promoting infiltration and reducing soil erosion (Dagnew et al., 2015; Mekonnen et al., 2015). The performance of soil and water conservation practices in the Ethiopian Highlands is of particular interest at the present time on account of government attempts to increase food self-sufficiency and the impending launch of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River (Hurni, 1988, 1999; Nyssen et al., 2009b; Dagnew et al., 2017; Walling, 2006; Walter et al., 1979). Since few watershed studies were carried out on the performance of the recently introduced soil and water conservation practices in the humid Highlands, we initiated a study in the Debre Mawi watershed located south of Lake Tana. The findings are applicable to all highlands where technocratic SWCPs were introduced without consideration of the indigenous practices.

We were interested in three specific areas where data were particularly sparse. First, there was some evidence that even governmental-sponsored SWCPs (such as 50 cm-deep infiltration furrows on the bunds either uphill or downhill) that are effective when first installed, can degrade rapidly with time (Tebebu et al., 2015; Zimale et al., 2017). The decreasing effectiveness was confirmed by Taye et al. (2015), who reported the evolution of the effectiveness of stone bunds and trenches for the reduction of runoff and soil loss in the semi-arid Ethiopian Highlands and concluded that these measures are only fully effective in the first year of their construction. The same study indicated that SWCPs are found to be influenced by the moisture regime and by the age of the structures. The performance of unmaintained structures decreases to 80% of the original value in the second year, 50% in the third year, and nearly 0% in the fourth year after implementation (Kato et al., 2011; Taye et al., 2015). Performance over time is a critical consideration for watershed rehabilitation projects, particularly considering the large-scale implementation that is currently taking place with the expectations of reductions in runoff leading to reductions in suspended sediment concentration (Tech, 2011).

Second, the long-term effectiveness of imported SWCPs has received very little study in the humid and sub-humid portions of the Ethiopian Highlands, as compared to studies of semi-arid zones (Hurni, 1988; Nyssen et al., 2004b; Haregeweyn et al., 2015). These more humid regions are characterized by high rainfall amounts, erodible soil, low drought risk, and productive soils. Land degradation has resulted in hardpan formation that shortens flow path of excess rainfall and increases saturation of bottomlands (Tebebu et al., 2015; Zimale et al., 2017). Analysis of SWCPs in the sub-humid and humid regions is particularly important as upland soil conservation strategies that are successful in semi-arid regions might lead to unintended erosion risk in more humid regions (Dagnew et al., 2015). This is because SWCPs that operate through increasing infiltration on hillslopes can lead to an increase in saturation in toe-slopes, weakening the soil matrix and increasing gully formation (Herweg and Ludi, 1999; Tilahun et al., 2014; Zegeye et al., 2016). Earlier reports from the watershed analyzed in the present study indicated that the contribution of bottomland gullies for catchment sediment losses is greater than that of upland erosion (Tebebu et al., 2010; Zegeye et al., 2014, 2018).

Third, while it is usually claimed by the experts that farming practices are detrimental for the environment, they overlook the fact that farmers benefit from reduced erosion as well and implement practices that may reduce soil loss (Guzman et al., 2018). Examples are the increase in eucalyptus tree cover (which has been observed widely) and rehabilitation of shallow gullies (Ayele et al., 2016). Quantitative evaluation of the farmer-led conservation efforts is especially scarce.

To gather additional data on these three aspects, we carried out the present nine-year study in the sub-humid Debre Mawi watershed to observe the spatial and temporal changes in runoff and sediment losses in relation to soil degradation, and government- and farmer-led conservation practices. Main assessment tools involved seasonal hydrometric measurement, field-scale observations of physical and chemical conditions of soil properties, and temporal analysis of observed soil degradation or restoration changes.

2. Materials and methods

2.1. The Debre Mawi watershed

The 716 ha Debre Mawi watershed (Fig. 1) is located in the sub-humid Ethiopian Highlands, Upper Blue Nile Basin, 30 km south of Bahir Dar along the road to Adet Town. The watershed is characterized as mountainous and of highly rugged and dissected topography with steep slopes (Guzman et al., 2018) and variable soil loss (Tilahun et al., 2013, 2015). The altitude ranges from 1950 m a.s.l. near the outlet to 2308 m a.s.l. in the southeast with slopes ranging from 1 to 30%. The watershed has a unimodal rainfall regime with an average annual rainfall of 1238 mm (Tebebu et al., 2010). June, July, August, and September receive around 80% of the annual rainfall. Potential evapotranspiration is 2–3 mm day^{-1} in the rain phase and 4–5 mm day^{-1} during the dry phase (Zegeye et al., 2016).

The watershed is underlain by shallow, highly weathered, and fractured basalt overlain by soil sequences. The fractures are highly interconnected with limited clay infillings but at some locations are blocked by lava dikes. The dikes running across the slope force the subsurface flow upward and enable formation of springs (Abiy, 2009; Tilahun et al., 2013a, 2013b). The soils in the Debre Mawi watershed consist of Nitisols, Vertisols and Vertic-Nitisols. Nitisols are fertile forested soils with high base saturation (>35%) and red, clay-loam soils covering the upper part of the watershed. These are very deep, well-drained, permeable soils and are well-suited for cereal cultivation. Vertisols are characterized as containing montmorillonite clay, which is a prominent member of the Smectite group, found in the bottom part of the watershed. The mid-slope of the watershed is dominated by Vertic Nitisols of reddish-brown color with good permeability and high moisture retention capacity. These soils are particularly well suited for tef (*Eragrostis abyssinica*) production (Abiy, 2009; Tilahun, 2012).

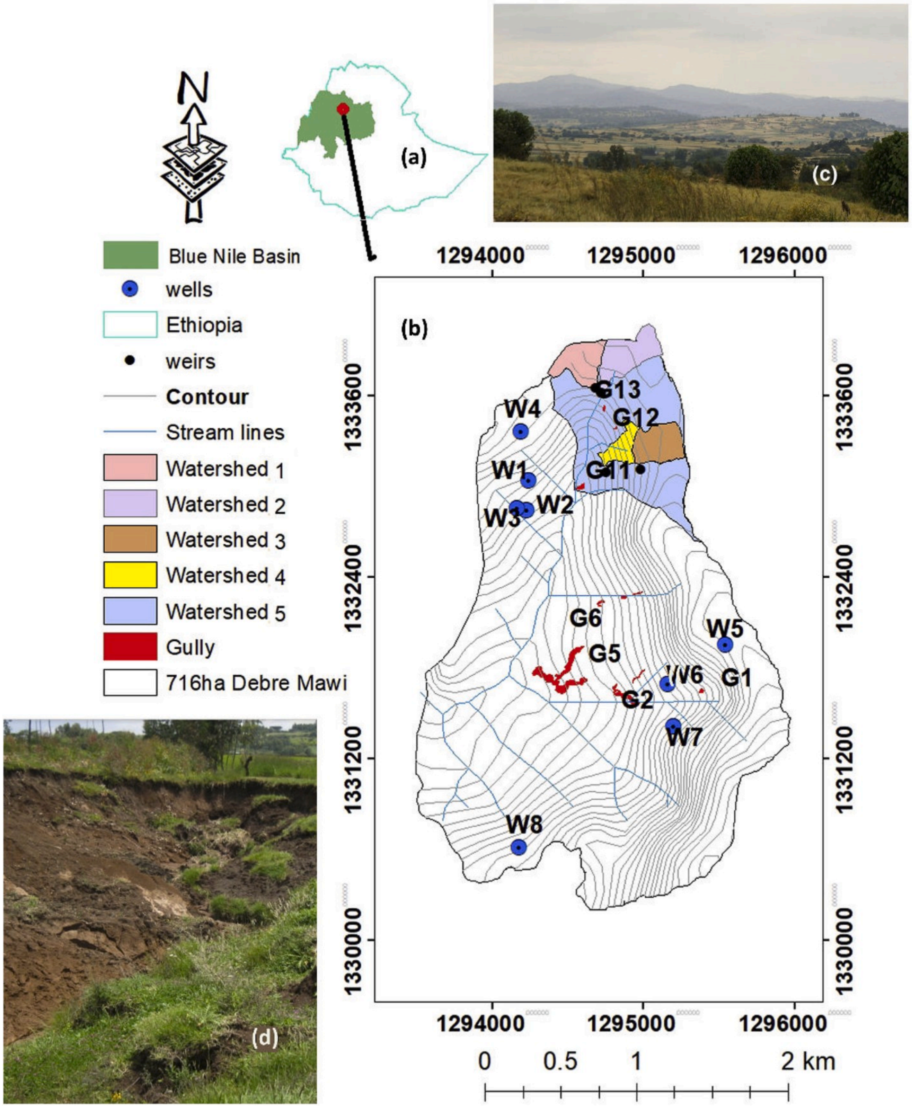

Fig. 1. The Debre Mawi Watershed. (a) Outline of Ethiopia with the Upper Blue Nile basin in green and the location of the watershed in red. (b) The 716 ha Debre Mawi watershed and the five nested watersheds; gullies studied are in red and indicated by the letter “G” followed by a number; blue dots are the wells indicated by the letter “W” and a number. (c) Photo of the Debre Mawi watershed showing the upland in the foreground and the saturated valley bottom in the middle; the mountains in the background are not a part of the watershed. (d) Lower part of gully G5. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

According to local residents, most of the watershed was forested with shifting cultivation fifty years ago (Tebebu et al., 2010). During the Derg Regime in the 1980s, trees were cut down by farmers and year-round cropping started. Currently, 75% of the watershed is cropped with cereals such as tef, maize (*Zea mays*), finger millet (*Eleusine coracana*), barley *(Hordeum vulgare*), and wheat (*Triticum aestivum*) (Abiy, 2009; Tebebu et al., 2010; Dagnew et al., 2015; Zegeye et al., 2016). The remaining landcover is grassland in the periodically saturated bottomland, shrubs on the shallow stony soils, and eucalyptus on erosive soils.

In the period from 2012 to 2014, soil and water conservation practices were constructed throughout the watershed by forced volunteer labor during January and February as part of the large-scale effort of the Ethiopian government to make the agriculture more productive. Physical measures include soil bunds with infiltration ditches that are on average 50-cm-deep, stone-faced soil bunds, and stone bunds. Biological measures to enhance the bund stabilization processes have been implemented as well. The most common biological measures consist of planting trees such as sasbania (*Sasbania grandiflora*) and grass species such as elephant grass (*Pennistum purpureum*). Farmers on their own initiative plant eucalyptus stands.

Several studies were performed in the Debre Mawi watershed related to soil loss and runoff. They consisted of runoff-erosion studies in the upper part of the watershed where active cultivation was taking place. In addition, we investigated in detail the effect of gully erosion on the sediment concentration in “conserved” areas of the watershed. We also documented the soil loss from gullies at the scale of the entire Debre Mawi watershed. Finally, we studied the effect of soil degradation on the hydrology of the landscape.

For the runoff and sediment loss studies, the upper 95 ha of the Debre Mawi watershed was divided into four nested sub-watersheds (Fig. 1). The area of the sub-watersheds was 8.8, 11, 6.5 and 10.4 ha, monitored at Weir 1, Weir 2, Weir 3 and Weir 4, respectively. The area upstream of Weir 1 has an area with periodically saturated grassland. The sub-watershed draining to Weir 2 is primarily cropland, and it also receives an unknown amount of storm runoff from the main asphalt road drainage ditch. Weirs 3 and 4 are on the same stream, with an area of periodically saturated grassland located between the two measurement locations. Weir 1, Weir 2, and Weir 3 are found above a set of lava dikes that interrupt the continuity of interflow. Weir 4 is below the lava intrusion dikes (Tilahun et al., 2015). Weir 5 is at the outlet of the 95-ha watershed (the northern portion of Debre Mawi).

2.2. Data collection

In the nine-year period from 2010 to 2018, precipitation during the rain phase was measured with an automatic tipping bucket rain gauge installed in the center of the upper watershed. In addition, discharge and suspended sediment concentrations at the outlet and the four nested watersheds were monitored (Table 1, Fig. 1). Flow depth and velocity were measured manually at weir sites, each at 10-min intervals during runoff events. To measure the velocity, a float was released 5 m upstream of the weir. The time taken for the float to reach the weir was recorded. Mean flow velocity was computed by multiplying the surface flow velocity by two-thirds (Chanson, 2004). Discharge was determined by multiplying the cross-sectional area of the stream by the mean velocity of flow (Tilahun et al., 2012). One-liter water samples were taken every 10 min for suspended sediment concentration until the water turned clear (Bosshart, 1995). Sediment concentrations were determined by filtering and weighing the mass of oven-dried samples on the filter (Walling, 1974). In all nested watersheds, runoff was only observed during rainfall events and shortly thereafter. Only at the outlet of the upper watershed did lateral flow occur during the last part of the rain phase. The data in 2010 and 2011 were obtained before the implementation of SWCPs, three years (from 2012 to 2014) of data were acquired during installation, and the data for four years, from 2015 to 2018, were obtained after the implementation. Stream discharge and suspended sediment concentration (SSC) were measured during storm events from June to September. Discharge and erosion were minimal during the dry phase (November to May). Soil erosion loss was calculated by multiplying observed discharge and suspended sediment concentrations for each 10-min interval and then summed for the event. Surveys of perched groundwater depth, bottomland saturated area, and bund conditions were also performed during selected years. In addition, a study was performed on the expansion of the gully network in 2013 and 2014 with detailed measurement on one of the gullies at which the discharge and the sediment concentrations were measured at its inlet and outlet over the two-year period. Using Google Earth images, we established that eucalyptus acreage tripled from 1.5 ha to 5 ha over the nine-year period. Finally, one study investigated land degradation by examining the soil properties of grasslands (i.e. pasture lands), cropland, and forested soils.

3. Result and discussion

In the Debre Mawi watershed, the rainy season is from late May to early October, and precipitation is heaviest in July and August. The average annual precipitation was 921 mm a^{-1} over the nine-year experimental period. The maximum rainfall of 1040 mm a^{-1} was in 2017 and minimum annual rainfall of 814 mm a^{-1} was in 2012 (Fig. 2). There is not a significant trend in the rainfall data for the nine years from 2010 to 2018 according to Mann-Kendall trend test, which yields a Kendall statistic of S = 16 and respective Mann-Kendall probability value of 0.06.

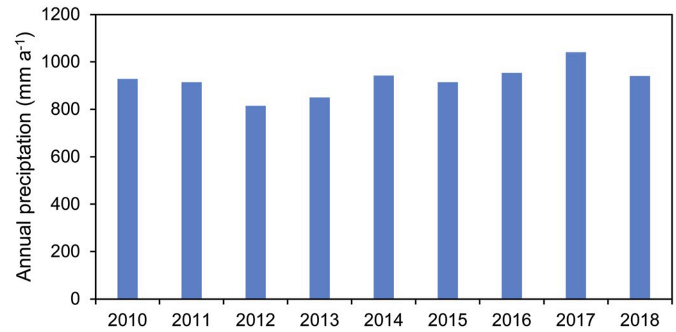

Fig. 2. Annual precipitation for the Debre Mawi watershed.

3.1. Soil degradation

Since deforestation in the 1980s, the soils in Debre Mawi watershed have been gradually degrading (Tebebu et al., 2015, 2017). To investigate the changes in the soil and hydrology due to land degradation, we compared the soil properties of samples taken within three land uses in 2014: cultivated, pasture, and forest lands, where forested land cover was a proxy for the original soil 40 years ago. Soil physical properties were measured down to 45 cm deep in three 15-cm increments throughout the watershed. Measurements consisted of soil penetration resistance, particle size, soil organic matter (SOM), pH, base ions, cation exchange capacity (CEC), silica content, bulk density, and moisture content (Tebebu et al., 2017). We found that in the cultivated and pasture lands, a slowly permeable soil layer was formed below the plowed soil to a depth of approximately 60 cm with penetration resistances above a threshold of 2000 kPa for root growth and bulk densities between 1.4 and 1.5 Mg m^{-3}. These dense layers did not occur in the undisturbed forested land where the bulk density was less than 1.0 Mg m^{-3}. Compared with the original forest soils, agricultural fields were: lower in organic matter, CEC, and exchangeable base cations; more acidic; had a higher bulk density and more fine particles (clay and silt); and contained less soluble silica (Tebebu et al., 2017). Plotting the data of the three land uses and depth together, a relationship was found between organic matter, the clay and silt particles, and the soil penetration resistance (Fig. 3). This relationship of increasing soil penetration resistance and greater amounts of fine particles implies that when the organic matter decreases below 3%, the aggregates break down or are transported off the field as erosion.

Land degradation has a major effect on the connectivity of the watershed. Initially, under forest cover and sometime thereafter, the soils are highly permeable with large macropores facilitating the infiltration of water (Tebebu et al., 2015; Zegeye et al., 2017). In time, once the soils become gradually finer, sediment concentration in the infiltrating water increases, and the macropores become clogged forming a hardpan, disconnecting the surface from the deep flow paths found in original forest soils. Once the pores are clogged sufficiently, and percolation rates become smaller than rainfall intensity, the surface 10–15 cm of plowed soils may become saturated during the rainstorm and water will flow laterally and overland downhill forming rills, thereby greatly increasing the sediment concentration in the water. Therefore, management practice interventions to decrease runoff and soil loss from the uplands should include practices that will increase long-term infiltration rates through the hardpans (Tebebu et al., 2015; Steenhuis and Tilahun et al., 2014). As we will see later, this affects gully formation as well.

Land degradation also affects gully formation (Zegeye et al., 2017). The increased direct runoff causes increased water table elevations

Table 1
Annual discharge (mm a^{-1}) for the main and nested Debre Mawi watersheds.

Watersheds	Discharge (mm a^{-1})								
	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	111	79	96	50	67	29	47	77	56
2	286	197	132	_	178	95	63	69	55
3	121	97	74	74	75	15	21	68	16
4	163	157	140	51	114	19	30	65	18
5	314	230	62	66	106	26	63	129	45

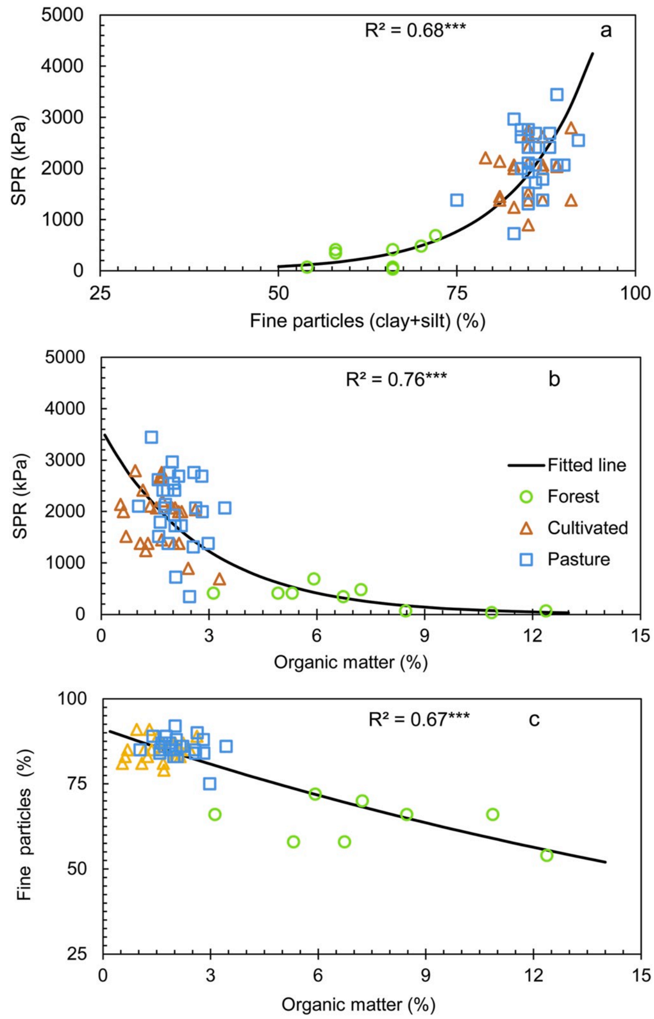

Fig. 3. Relationships of organic matter, soil penetration resistance, and fine (clay and silt) particles for forest, pasture and cropland in the Debre Mawi Watershed: (a) soil penetration resistance (SPR) vs fine particles consisting of silt and clay; (b) SPR vs organic matter content; and (c) silt and clay particles vs organic matter (Tebebu et al., 2017). R^2 is the regression coefficient. The *** indicates that the relationships have a significance of 99%.

(more shallow and saturated) in the valley bottomlands (Tebebu et al., 2010; Zegeye et al., 2016), thereby weakening the soil strength and erosion resistance. This allows gullies to form to carry off additional water, lowering the water table so that a new equilibrium is achieved. We will discuss these dynamics further in the next section.

3.2. Hydrology

In this section, we will first discuss the spatial and temporal distribution of the perched groundwater in the watershed during, and a short time after, the rain phase as it has a major impact on both runoff and gully formations. This is followed by a discussion on direct runoff and runoff ratio.

3.2.1. Groundwater level

Groundwater levels were observed by Alemie et al. (2019) in 8 hand dug wells throughout the entire watershed in 2016 and 2017. Earlier, Guzman et al. (2017a) observed water tables in Watershed 2. Both studies found that the water tables were directly related to the landscape position. Near the watershed divide, levels increased during a sufficiently large rainstorm and then fell shortly afterwards to near the bedrock (Guzman et al. (2017a), not shown). For bottomlands, water tables started to rise in wells after the first rain (W5 and W7 in Fig. 4) and reached the surface around the middle of July (Alemie et al., 2019). The rise is only shown for W5; measurements started too late to show the increase in water table in W7. The groundwater stayed near the surface until the end of the rain phase in September (W5) and beginning of November (W7), and then declined (Alemie et al., 2019). The behavior of the water tables on mid-slope (W2 and W3 in Fig. 1) varied between the two extremes near the watershed divide and river. On the mid-slope position, the perched groundwater level was strongly dependent on the amount of rainfall, and water levels could be predicted accurately by summing the recharge over the travel time from the watershed divide to the well and dividing by the drainable porosity (Alemie et al., 2019). The calculated travel time for W2 was 75 days and for W3, 55 days with a drainable porosity of 4%.

The subsurface flows mainly, and to some degree the surface flows, are the causes behind saturation in the valley bottoms. In our August 2017 survey, we found that the saturated area in the watershed (in which the water table was at or near the surface) at the beginning of August was delineated as 27% of the upper watershed (Fig. 5). These are the areas that are covered with grass. While saturation temporally expands during a large rainfall event and contracts during long dry periods, the size of the wet areas remains relatively constant and only contracts permanently after the rainy season ends. In the middle of November, the water table is below the surface in the entire watershed.

3.2.2. Direct runoff and runoff coefficient

The average annual runoff over the nine-year period was 116 mm a^{-1} for the entire upper watershed and 86 mm a^{-1} for the four nested watersheds (Table 1). The maximum annual direct runoff for all plots took place in 2010 with above average rainfall of 921 mm a^{-1} (Fig. 2). Minimum annual discharge occurred in either 2015 or 2018, years with below average rainfall (Table 1). Trend analysis with the Mann-Kendall test indicated there was a general decrease in runoff but it was only significant at the 5% probability level for nested watersheds two and three.

The runoff coefficient, that is, the ratio of runoff to rainfall, is a measure to quantify how much of the incoming rainfall is converted to catchment runoff. The maximum runoff coefficient was found in the main watershed (0.34) in 2010, before SWCP implementation, and the minimum was 0.05 in 2018, after SWCP implementation (Fig. 6). The decrease in runoff coefficient was significant at the 5% probability level for sub-watersheds 2–5 and not significant at 5% for nested watershed 1. The advantage of using the runoff coefficient is that it is less dependent on the variability of rainfall.

Table 1 and Fig. 6 show that Watershed 2 has a different pattern of discharge because some of the discharge originated from the road

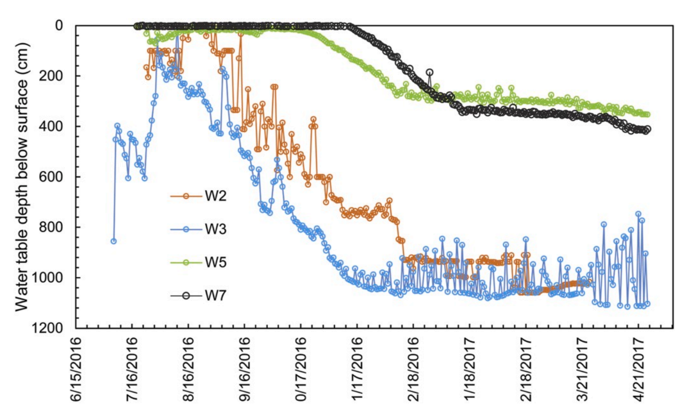

Fig. 4. Groundwater levels in the Debre Mawi watershed. Wells W2 and W3 are located midslope and W5 and W7 are located downslope. During the rain phase, the piezometer readings are either at or near the surface indicating that soil is saturated.

Fig. 5. Saturated area of the Debre Mawi Watershed in 2017. The red line is the boundary of Debre Mawi upper watershed 5, while the blue is the saturated area. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

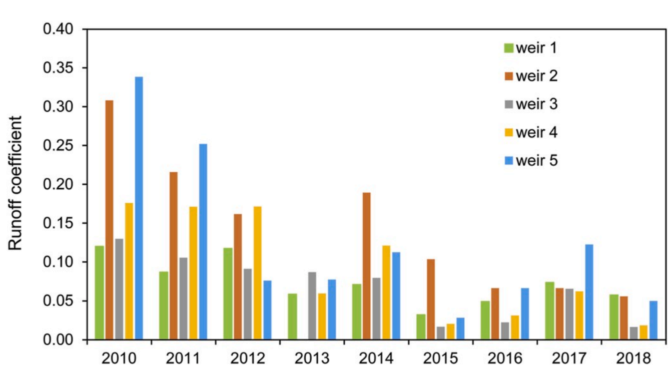

Fig. 6. Runoff-rainfall ratio (runoff coefficient) for the Debre Mawi watershed.

(Guzman et al., 2017b). There were road improvements from 2013 to 2016 and the drainage pattern of the road was affected by the change from initial unpaved road conditions to an asphalt road.

In addition, Table 1 and Fig. 6 show that the discharge per unit area and the runoff coeffiecients respectively in Weir 5 at the upper watershed outlet (which collects water from the other four weirs) is frequently greater per unit area for all years except 2012 - 2014 than Weirs 3 and 4 which were not affected by road runoff. Weir 5 discharge is greater than Weir 1, except in 2012, 2015 and 2018. The reason is that those nested weirs are located further upland with relatively small saturated areas during the rain phase. Weir 5 is located in the saturated valley bottom (Photo 1c shows watershed with the valley bottomlands and Fig. 5 shows the saturated area in August) with an elevated water table close to the surface during most years, usually starting in July of the rain phase until the beginning of October. Unlike the upper subwatersheds, the water within the bottomlands of watershed 5 cannot infiltrate into the saturated soil (despite its high saturated conductivity). Hence, direct runoff is generated as saturation-excess overland flow. In dry years, such as in 2012, saturation occurs late during the dry phase and downstream area upstream of Weir 5 acts as a sink for runoff of the upper sub-watersheds for an extended period and hence the reduced runoff compared to other years.

3.3. Suspended sediment concentration and total soil loss

3.3.1. Entire watershed: effect of gullies

Zegeye et al. (2017) calculated the soil transported from 13 gullies in 2013 and 2014 by measuring the change in area and depth (Fig. 1 shows the locations of the gullies). As can be seen from Fig. 1, the gullies in the Debre Mawi watershed are not in the steepest parts of the landscape, but rather at the lower, relatively flatter elevations in the watershed. The amount of soil removed in 2013 and 2014 was on average 20 Mg ha^{-1} a^{-1} over the entire watershed and 50 Mg ha^{-1} a^{-1} when the only watershed areas considered were those which drained directly into gullies. There was a large intra-gully variation in the soil transported. Gully 6 alone was approximately responsible for half of all the 5 Gg a^{-1} transported out of the gully, and Gully 5 accounted for 25% of soil loss. Two gullies in the upper watershed (Gully 12 and Gully 13) contributed 0.3% of the total loss during 2013–2014. Before 2013, these two gullies expanded more rapidly (Tilahun et al., 2015; Zegeye et al., 2014).

As shown by Tebebu et al. (2010) and by Zegeye et al. (2016), gullies are expanding in locations where the water table is above the gully bottom. An example is given for the northern branch of Gully 6 (Tebebu et al., 2010) where the change in gully width was the greatest between the distances of 200 m–300 m upslope of the downstream end, where the water table was above the gully bed (Fig. 7). Saturated soils have high pore-water pressure and lower cohesive strength. This makes a saturated watershed more prone to bank slipping (Assefa et al., 2015; Mhiret et al., 2018), particularly in a sub-humid monsoonal climate.

To find the effect of gullies on sediment concentrations, Zegeye et al. (2017) monitored suspended sediment concentration and sediment load upstream and downstream of Gully 6 for two years and found that suspended sediment concentration at the outlet of the gully was approximately an order of magnitude greater than at the inlet (Fig. 8). Zegeye et al. (2017) calculated that 90% of the sediment at the outlet originated from the gully itself and only 10% from the upland. Thus, the gully greatly affected suspended sediment concentrations.

3.3.2. Upper watershed sediment loss

Suspended sediment concentrations were measured in storm runoff at the outlet of the upper watershed and the four nested watersheds within a nine-year period. The average annual suspended sediment concentration (g L^{-1}) is presented in Fig. 9. The Mann-Kendall trend test results show that the observed sediment concentration decreased for all five weirs at a probability level of less than $\alpha = 0.012$ leading us to accept the hypothesis of a significant decreasing trend for suspended

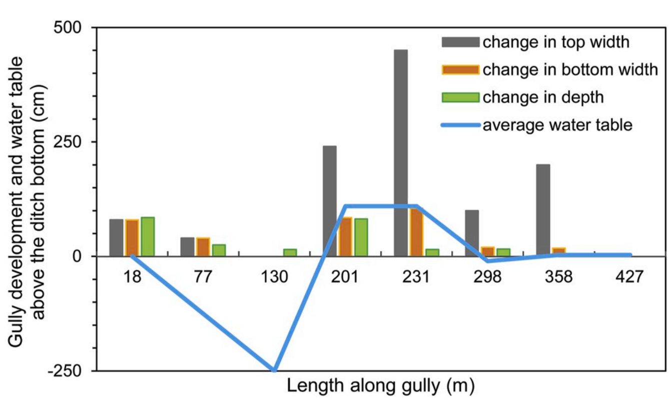

Fig. 7. Change in top and bottom width and depth of the gully before and after the 2008 rain phase for the northern branch of Gully 6 (Tebebu et al., 2010).

sediment concentration at all weirs. In addition, Fig. 9 shows that the sediment concentration in Weir 5 (found in the valley bottom that collects water and sediment from the other four upland watersheds) is significantly greater than that observed at the other weirs. Sediment concentration for Watershed 2, which collects drainage from the road as well is also highly elevated during the first two years. The suspended sediment concentrations patterns for the weirs in the four sub-watersheds are very similar within a year compared to the variation between years.

As expected from the amount of direct runoff in Fig. 6 and sediment concentrations in Fig. 9, the amount of sediment lost from Watershed 5 is greater than its upland parts (Fig. 10). The temporal trend in sediment loss is decreasing but not significantly, except for the nested watersheds two and three, indicating that the amount of runoff is more important for total sediment loss than the sediment concentration, which had a significant downward trend for all watersheds.

Although the soil lost from the gullies is not necessarily the same as that flowing over the weir, the measured amount lost at Weir 5 (13.3 Mg ha^{-1} a^{-1} in 2013 and 12.5 Mg ha^{-1} a^{-1} in 2014) was less than that lost from the gullies in the downstream part of the watershed, which was 20 Mg ha^{-1} a^{-1}, as Gullies 12 and 13, located in the upper part, were relatively stable. In addition, there was another gully that formed during and after the installation of the soil and water conservation practices but was not measured by Zegeye et al. (2017). This gully expanded rapidly. Despite the upland SWCPs, soil loss increased as the valley bottom runoff flowed through unconsolidated sediments in the gullies (originating from the failing banks in both gullies), which in combination with greater amounts of runoff (Table 1) and greater stream power, made it easier to pick up additional sediment.

Another sediment contributor was the unpaved road that drained through Weir 2. It had the second highest sediment concentration in 2010 and third in 2011 (Fig. 9) and greater amounts of runoff than any of the nested watersheds during these years (Fig. 6; Guzman et al., 2017a,b).

4. Effect of governmental-sponsored and farmer-led land management practices

In the previous section, we noted the importance of the perched groundwater table on the hydrology, gully formation, and soil loss. We will therefore first discuss the effect of government sponsored infiltration furrows and bunds on the water table followed by how land management practices (both farmer initiated and governmental sponsored) have an effect first on the hydrology and then on the suspended sediment concentrations and soil loss.

To study the perched groundwater table, we installed six sets of piezometers 5 m uphill and 5 m downhill of rehabilitated infiltration furrows to track the change in water table during the 2018 rain phase. Two sets were installed in midslope positions, and four sets in downslope portion.

The depths of the perched water tables are given in Fig. 11. The overall behavior of the water levels in the upper watershed was as expected, similar to that observed by Alemie et al. (2019; Fig. 4) in 2016 and 2017 in other parts of the watershed and Guzman et al. (2017a) in the upper part in 2015. For the piezometers at the midslope positions (Fig. 11a and b), the water table intercepts a large portion of the infiltrated rainfall and rises slowly, then decreases after the rainfall ceases. The groundwater level in the piezometers located uphill from the saturated area (Fig. 11c and d) are close to the surface, but the height is dependent on the amount of previous rainfall. Fig. 11e and f shows that the water table for piezometers at the boundary of the saturated area is at the surface for an extended period during the middle and last part of the rain phase.

Comparing the piezometer pairs in Fig. 11, we note that in four cases (Fig. 11 a,d,e,f), the piezometer downhill of the infiltration furrow had a water table that is closer to surface than at the uphill of the furrow. Thus,

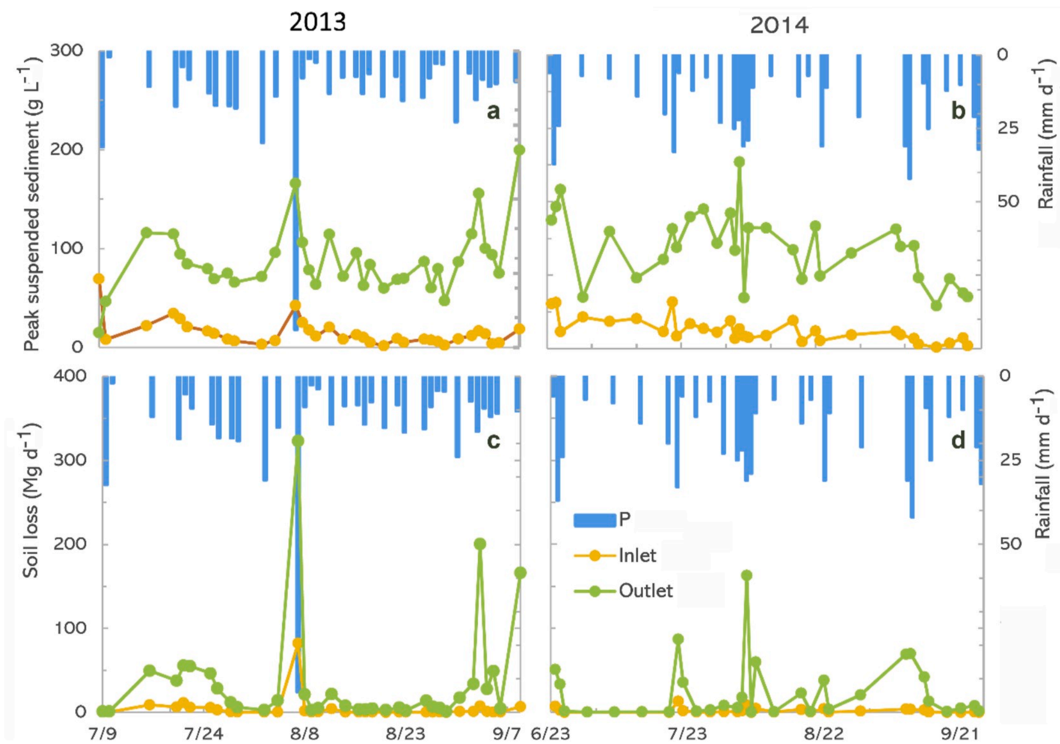

Fig. 8. Sediment concentrations and soil loss at the inlet (orange) and outlet (green) of Gully 6 in the Debre Mawi watershed (Zegeye et al., 2017): (a) sediment concentrations in the 2013 rain monsoon phase, (b) sediment concentrations in the 2014 rain monsoon phase, (c) daily soil loss in the 2013 rain monsoon phase, and (d) daily soil loss in the 2014 rain monsoon phase. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

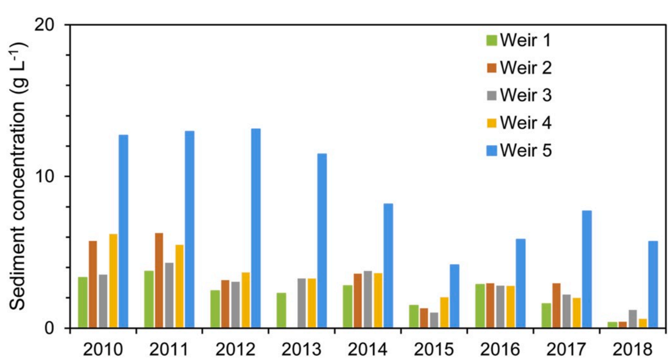

Fig. 9. Observed mean-annual suspended sediment concentration in the upper watershed (Weir 5) and four nested watersheds (Weirs 1–4) in Debre Mawi.

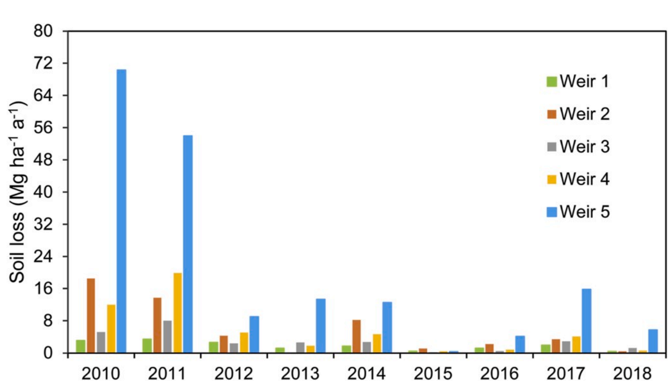

Fig. 10. Annual soil loss in the main upper watershed (Weir 5) and four nested watersheds (Weirs 1–4) in Debre Mawi.

the amount of water infiltrating was minimal at best because otherwise the water table would have been deeper downslope of the furrow rather than at the uphill locations. In one case, for the midslope region (Fig. 11b), water was infiltrating into the subsoil lowering the water table downslope of the furrow compared to upslope. This case highlights an example of the SWCP functioning as advertised. In Fig. 11c, the piezometer water levels were almost at the same depth below the surface and the infiltration furrow did not have an effect.

As noted earlier in the section on gully erosion, saturated soil has very little strength and easily fails. That was also the case for the furrow near the set of piezometers in Fig. 11e that lost 72% of its capacity in 12 days after being restored to its original depth (Fig. 12b).

In the saturated bottomland, another infiltration furrow resulted in a large gully downhill. In this case, the infiltration furrow acted as a cutoff drain collecting water that was flowing downhill. The concentrated flow started a large gully shortly after construction in 2012 that was 56 m long and 4 m wide in 2018. In Fig. 12a, the infiltration furrow and start of the gully is depicted. This gully was one of the gullies that contributed to Weir 5 at the outlet of the upper watershed having greater sediment concentrations than those measured in the nested watersheds.

One clear mismanagement practice related to SWCPs in the watershed is the presence of bunds in the saturated bottomlands. While bunds may be effective at reducing upland erosion, in the bottomlands they contribute directly to saturation (Herweg and Ludi, 1999) and risk of gully formation (Fig. 12a), while providing little sustainable benefit in sediment retention (Fig. 9b). After the installation of bunds, reduction of soil loss was observed in the short-term. However, in the periodically saturated bottomlands, bunds were filled up within two years. Mitiku et al. (2006) recommended planting trees on the bunds to maintain the furrows. However, since the soil has very little cohesive strengths when saturated, it is unlikely that for the first years, the roots of trees can prevent filling of the bunds.

To investigate the effect of the implementation of government

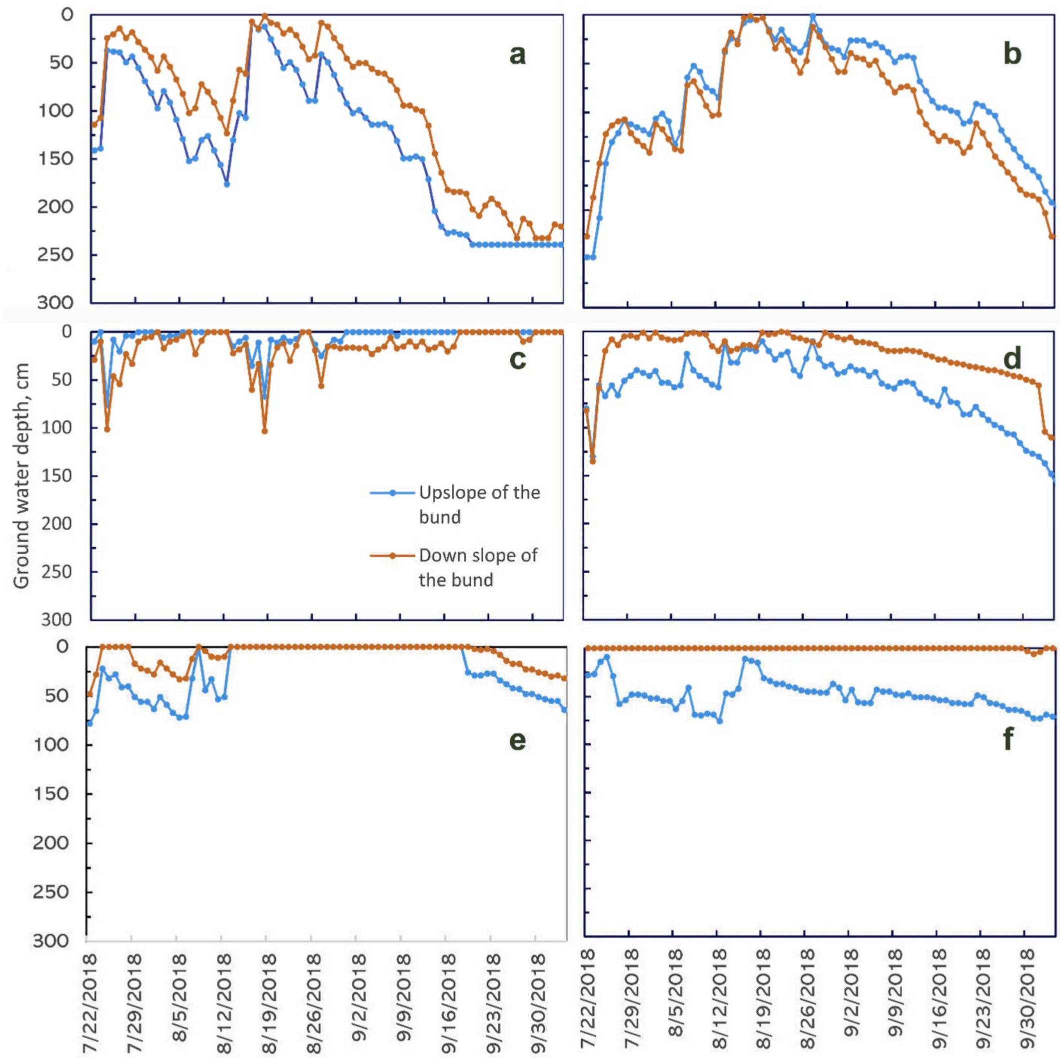

Fig. 11. Perched groundwater table depth from the surface for the six piezometer pairs installed in the 95-ha upper portion of the watershed: Blue is upslope and orange is downslope of the bund. (a, b) Piezometer pairs located midslope; (c, d) Piezometer pairs located slightly above of saturated area; (e, f) Piezometer pairs bordering, or in, the saturated area. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 12. (a) Gully that formed due to improper positioning of bunds in saturated bottomland and, (b) a level bund that lost 72% of its capacity in 12 days after maintenance in the upper part of the Debre Mawi watershed.

sponsored and farmer-led land management practices on discharge, we divided the study period into pre-SWCP years (2010–2011), transition years during implementation (2012–2014), and post-SWCP years (2015–2018). Viewed in these categories, a clear pattern of reduced runoff and sediment concentration emerges during and after construction of the soil and water conservation practices (Fig. 13).

These observation would suggest that upland government sponsored SWCPs are the only reason for the decrease in runoff in Debre Mawi (Fig. 13 a,b). However, this might be too optimistic in this sub-humid environment considering the other changes taking place in the watershed as well, which may have a similar or even more dominant role. In addition to the installation of practices, the eucalyptus acreage more than tripled to 5 ha in 2018. Interviews with farmers revealed that the eucalyptus trees were planted on land that was too wet or eroded for growing crops and thereby protected the land against erosion.

Eucalyptus affects the hydrology greatly because it has substantially higher evapotranspiration than the fallow land and causes a reduction in streamflow and groundwater storage (Enku et al., 2014; Chanie et al., 2013). Eucalyptus has roots that can reach the moisture stored deep in the soil and when planted in patches, the trees can evaporate twice the potential rate during the dry phase due to the convective heat from the dry wind (Enku et al., 2020). Thus, before the rain phase starts, there is more storage in the watershed for rain to infiltrate before the soil becomes saturated and direct runoff is initiated. Hence, eucalyptus trees will lower the discharge from the watershed and might be the reason that the runoff coefficient is decreasing (Fig. 13b). It should be noted that location of infiltration furrows had very little local (community) input while the locations of the eucalyptus trees were chosen after crop production became impossible.

In addition, road construction had a significant impact on the decline in runoff coefficient in Watershed 2. The runoff was routed differently and some road runoff was diverted to Watershed 1 in which the runoff coefficient decreased less relative to the other watersheds in 2017 and 2018 (Fig. 13 b).

Finally, since the sediment concentration is directly related to the discharge (Tilahun et al., 2015), the decrease in suspended sediment concentration (Fig. 13c) is likely more related to the decreased flows than the filled-up infiltration furrows. In addition, the planting of eucalyptus trees on the most vulnerable lands (that were full grown by 2018), might have decreased the sediment concentration as well. The decrease in soil loss over time (shown in Fig. 13d) was the result of both the decreased runoff and sediment concentration.

Thus, the government sponsored SWCPs, consisting of infiltration furrows and bunds, were not solely responsible for a smaller portion of the rainfall being transported out of the basin as direct runoff, but rather all three factors (i.e. SWCPs, eucalyptus tree planting, and road construction). The increased storage for water at the beginning of the rainy season, due to the evapotranspiration of the eucalyptus, likely had the greatest impact since all infiltration furrows were filled in by 2018.

5. Conclusion

This study aims to understand the effect of SWCPs in the Debre Mawi watershed based on long-term field observations. Precipitation, stream discharge, and suspended sediment concentrations were recorded for all major runoff events over a nine-year period. In addition, groundwater table depth and total saturated area measurements were taken for selected periods. All observations are consistent with the interpretation that SWCPs are, to date, effective in reducing upland soil loss. The runoff coefficient has been reduced across the watershed, as has the concentration of sediment in storm flow. Trend tests indicate that these reductions are statistically significant over the period of analysis. At the same time, the measurements also suggest an increasing risk of erosion in bottomlands, as piezometer measurements and surveys of saturated area indicate that there is an increase in infiltration associated with SWCPs that is leading to greater saturation and potential soil weakening in gully-prone toe slopes of the watershed. Field observation and photo analysis also suggested that some SWCPs were ineffective and potentially problematic. This was particularly clear for bunds installed in bottomlands, where they quickly filled with sediment and exacerbated problems of soil saturation.

We note that the trends in observed data may be influenced by factors other than SWCPs, especially in the upper watersheds. For example, there has been an expansion of eucalyptus plantations in the watershed, from 1.5 ha in 2010 to 4.5 ha in 2018. This is similar to the wide expansion of eucalyptus found in other areas of the Blue Nile Highlands in this period (Yimanie et al., 2019). Eucalyptus has high evapotranspiration rates and can access deeper soil moisture that is inaccessible to annual crops, which could contribute to the reduction in runoff ratio and, potentially, sediment concentrations. We also note that while nine

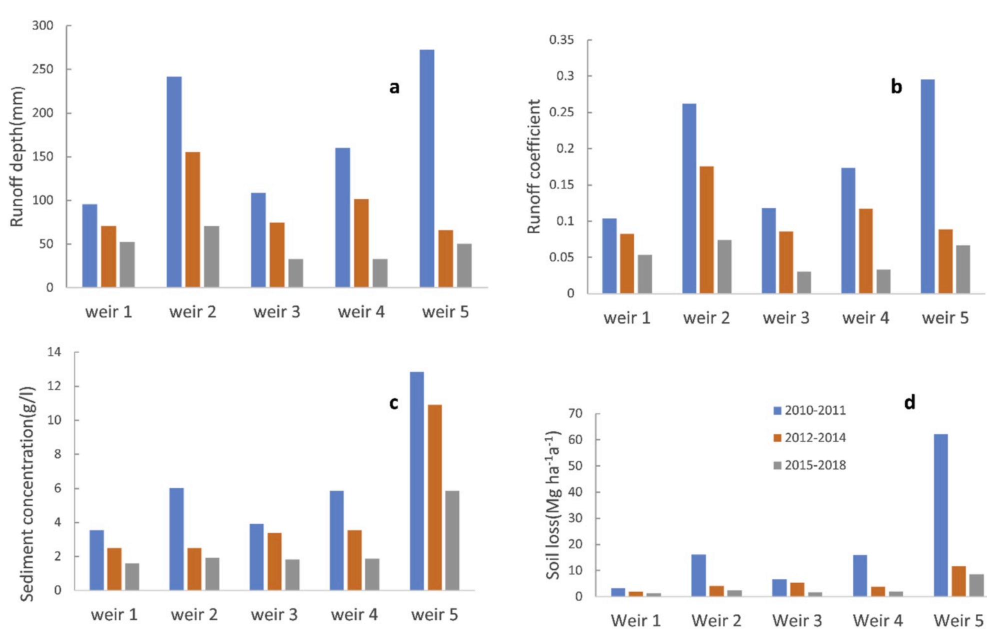

Fig. 13. Discharge and sediment losses from the upper Debre Mawi watershed before, during and after implementation of government sponsored soil and water conservation practices: a) discharge; b) runoff coefficient; c) suspended sediment concentration; and d) soil loss.

years is a long record by the standards of available data in the Ethiopian Highlands, it is quite possible that trends will shift in the future if SWCPs are not maintained and/or if the observed increase in saturation of toe slopes results in a large increase in gully erosion.

Notwithstanding these limitations, the results of this observational study point to both the potential benefits of SWCPs in this sub-humid tropical highland region and to emerging long-term risks. If SWCPs are to be pursued in watersheds like Debre Mawi, due attention has to be given to the safe removal of excess water from the valley bottoms. This can be accomplished through context-appropriate SWCPs siting, careful attention to drainage in addition to sediment trapping, and/or integration of vegetation in a manner that offsets increased water infiltration.

Declaration of competing interest

The authors declare that they do not have a conflict of interest.

CRediT authorship contribution statement

Demesew A. Mhiret: Data curation, Formal analysis, Writing - original draft. **Dessalegn C. Dagnew:** Data curation, Formal analysis, Writing - original draft, Supervision, Writing - review & editing. **Christian D. Guzman:** Data curation, Formal analysis, Writing - original draft. **Tilashwork C. Alemie:** Data curation, Formal analysis, Writing - original draft. **Assefa D. Zegeye:** Data curation, Formal analysis, Writing - original draft. **Tigist Y. Tebebu:** Data curation, Formal analysis, Writing - original draft. **Eddy J. Langendoen:** Writing - review & editing. **Benjamin F. Zaitchik:** Supervision, Writing - review & editing, Formal analysis. **Seifu A. Tilahun:** Data curation, Formal analysis, Writing - original draft, Supervision, Writing - review & editing. **Tammo S. Steenhuis:** Supervision, Writing - review & editing, Formal analysis.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110885.

References

Abate, M., Nyssen, J., Steenhuis, T.S., Moges, M.M., Tilahun, S.A., Enku, T., Adgo, E., 2015. Morphological changes of gumara river channel over 50 years, upper blue Nile Basin, Ethiopia. J. Hydrol. 525, 152–164.

Abiy, A.Z., 2009. Geological Controls in the Formations and Expansions of Gullies over Hillslope Hydrological Processes in the Highlands of Ethiopia, Northern Blue Nile Region. Cornell University (MPS thesis.

Alemie, T.C., Tilahun, S.A., Ochoa-Tocachi, B.F., Schmitter, P., Buytaert, W., Parlange, J.-Y., Steenhuis, T.S., 2019. Predicting shallow groundwater tables for sloping highland aquifers. Water Resour. Res. 55 https://doi.org/10.1029/2019WR025050.

Assefa, T.T., Jha, M.K., Tilahun, S.A., Yetbarek, E., Adem, A.A., Wale, A., 2015. Identification of erosion hotspot area using GIS and MCE technique for Koga watershed in the Upper Blue Nile Basin, Ethiopia. Am. J. Environ. Sci. 11 (4), 245.

Ayele, G.K., Gessess, A.A., Addisie, M.B., Tilahun, S.A., Tebebu, T.Y., Tenessa, D.B., Langendoen, E.J., Nicholson, C.F., Steenhuis, T.S., 2016. A biophysical and economic assessment of a community-based rehabilitated gully in the Ethiopian highlands. Land Degrad. Dev. 27, 270–280. https://doi.org/10.1002/ldr.2425.

Bosshart, U., 1995. Catchment Discharge and Suspended Sediment Transport as Indicators of Physical Soil and Water Conservation in the Minchet Catchment, Gojam Research Unit: A Case Study in the North-Western Highlands of Ethiopia, Soil Conservation Research Programme Research Report. University of Bern, Switzerland, 1995.

Chanie, T., Collick, A.S., Adgo, E., Lehmann, C.J., Steenhuis, T.S., 2013. Eco-hydrological impacts of Eucalyptus in the semi humid Ethiopian highlands: the lake tana plain. J. Hydrol. Hydromech. 61, 21–29.

Cheesman, R.E., 1936. Lake Tana & the Blue Nile: an Abyssinian Quest. Macmillan and Co, New York, p. 400.

Chanson, H., 2004. Hydraulics of Open Channel Flow. Elsevier, Amsterdam, 650.

Constable, M., Belshaw, D., 1986. December. The Ethiopian Highlands reclamation study: major findings and recommendations. Towards a food and nutrition strategy for Ethiopia: Proceedings of the national workshop on food strategies for Ethiopia. In: ONCCP (Office of the National Committee for Central Planning), pp. 8–12.

Dagnew, D.C., Guzman, C.D., Akale, A.T., Zegeye, A.D., Mekuria, W., Tilahun, S.A., Steenhuis, T.S., 2017. Effects of land use on catchment runoff and soil loss in the sub-humid Ethiopian highlands. Ecohydrol. Hydrobiol. 4, 274–282. https://doi.org/10.1016/j.ecohyd.2017.07.004.

Dagnew, D.C., Guzman, C.D., Zegeye, A.D., Tebebu, T.Y., Getaneh, M., Abata, S., Zimale, F.A., Ayana, E.K., Tilahun, S.A., Steenhuis, T.S., 2015. Impact of conservation practices on runoff and soil loss in the sub-humid Ethiopian Highlands: The Debre Mawi watershed. J. Hydrol. Hydromech. 210–219. https://doi.org/10.1515/johh-2015-0021.

Enku, T., Tadesse, A., Yilak, D.L., Gessesse, A.A., Addisie, M.B., Abate, M., Zimale, F.A., Moges, M.A., Tilahun, S.A., Steenhuis, T.S., 2014. Biohydrology of low flows in the humid Ethiopian Highlands: the Gilgel Abay catchment. Biologia 69 (11), 1502–1509.

Guzman, C.D., Tilahun, S.A., Dagnew, D.C., Zegeye, A.D., Tebebu, T.Y., Yitaferu, B., Steenhuis, T.S., 2017. Modeling sediment concentration and discharge variations in a small Ethiopian watershed with contributions from an unpaved road. J. Hydrol. Hydromech. 65 (1), 1–17. https://doi.org/10.1515/johh-2016-0051.

Guzman, C.D., Tilahun, S.A., Dagnew, D.C., Zimale, F.A., Zegeye, A.D., Boll, J., Parlange, J.-Y., Steenhuis, T.S., 2017. Spatio-temporal patterns of groundwater depths and soil nutrients in a small watershed in the Ethiopian Highlands: topographic and land-use controls. J. Hydrol 555, 420–434. https://doi.org/10.1016/j.jhydrol.2017.09.060.

FAO, 1986. Ethiopian Highland Reclamation Study. Volume 1. Food and Agriculture Organization of the United Nations, Rome.

Guzman, C.D., Tilahun, S.A., Zegeye, A.D., Yitaferu, B., Kay, R.W., Nagle, G.N., Steenhuis, T.S., 2018. Developing soil conservation strategies with technical and community knowledge in a degrading sub-humid mountainous landscape. Land Degrad. Dev. 29 (3), 749–764. https://doi.org/10.1002/ldr.2733.

Haregeweyn, N., Tsunekawa, A., Nyssen, J., Poesen, J., Tsubo, M., Tsegaye Meshesha, D., Schütt, B., Adgo, E., Tegegne, F., 2015. Soil erosion and conservation in Ethiopia: a review. Prog. Phys. Geogr. 39 (6), 750–774.

Herweg, K., Ludi, E., 1999. The performance of selected soil and water conservation measures—case studies from Ethiopia and Eritrea. Catena 36 (1–2), 99–114.

Hurni, H., 1988. Degradation and Conservation of the Resources in the Ethiopian Highlands. Mountain research and development, pp. 123–130.

Hurni, H., 1993. Land degradation, famine, and land resource scenarios in Ethiopia. In: Pimentel, D (Ed.), World Soil Erosion and Conservation, Cambridge Studies in Applied Ecology and Resource Management. Cambridge University Press, Cambridge, pp. 27–62.

Kato, E., Ringler, C., Yesuf, M., Bryan, E., 2011. Soil and water conservation technologies: a buffer against production risk in the face of climate change? Insights from the Nile basin in Ethiopia. Agric. Econ. 42 (5), 593–604.

Mekonnen, M., Keesstra, S.D., Baartman, J.E., Ritsema, C.J., Melesse, A.M., 2015. Evaluating sediment storage dams: structural off-site sediment trapping measures in northwest Ethiopia. Cuadernos de investigación geográfica 41 (1), 7–22.

Mhiret, D.A., Dagnew, D.C., Assefa, T.T., Tilahun, S.A., Zaitchik, B.F., Steenhuis, T.S., 2018. Erosion hotspot identification in the sub-humid Ethiopian Highlands. Ecohydrol. Hydrobiol. 19, 146–154.

Mitiku, H., Herweg, K.G., Stillhardt, B., 2006. Sustainable Land Management: A New Approach to Soil and Water Conservation in Ethiopia.

Moges, M.A., Tilahun, S.A., Ayana, E.K., Moges, M.M., Gabye, N., Giri, S., Steenhuis, T.S., 2016. Non-point source pollution of dissolved phosphorus in the Ethiopian Highlands: the Awramba watershed near Lake Tana. Clean 44 (6), 703–709.

Nyssen, J., Haile, M., Naudts, J., Munro, N., Poesen, J., Moeyersons, J., Frankl, A., Deckers, J., Pankhurst, R., 2009. Desertification? Northern Ethiopia re-photographed after 140 years. Sci. Total Environ. 407 (8), 2749–2755.

Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., Lang, A., 2004. Human impact on the environment in the Ethiopian and Eritrean Highlands—a state of the art. Earth Sci. Rev. 64 (3–4), 273–320.

Pretty, J.N., Shah, P., 1997. Making soil and water conservation sustainable: from coercion and control to partnerships and participation. Land Degrad. Dev. 8, 39–58.

SCRP, 2000. Area of Gununo, Sidamo, Ethiopia: Long-Term Monitoring of the Agricultural Environment (1981-1994), Soil Conservation Research Project (SCRP). Center for Development and Environment (CDE), University of Bern, Switzerland.

Shiferaw, B., Holden, S., 1999. Soil erosion and smallholders' conservation decisions in the Highlands of Ethiopia. World Dev. 27 (4), 739–752.

Tato, K., Hurni, H., 1992. Soil conservation for survival. 6th International Soil Conservation Conference,(Ethiopia), 1989. Soil and Water Conservation Society.

Taye, G., Poesen, J., Vanmaercke, M., van Wesemael, B., Martens, L., Teka, D., Nyssen, J., Deckers, J., Vanacker, V., Haregeweyn, N., Hallet, V., 2015. Evolution of the effectiveness of stone bunds and trenches in reducing runoff and soil loss in the semi-arid Ethiopian Highlands. Z. Geomorphol. 59 (4), 477–493.

Tebebu, T.Y., Abiy, A.Z., Zegeye, A.D., Dahlke, H.E., Easton, Z.M., Tilahun, S.A., Collick, A.S., Kidnau, S., Moges, S., Dadgari, F., Steenhuis, T.S., 2010. Surface and subsurface flow effects on permanent gully formation and upland erosion near Lake Tana in the northern Highlands of Ethiopia. Hydrol. Earth Syst. Sci. 14, 2207–2217.

Tebebu, T.Y., Bayabil, H.K., Stoof, C.R., Giri, S.K., Gessess, A.A., Tilahun, S.A., Steenhuis, T.S., 2017. Characterization of degraded soils in the humid Ethiopian Highlands. Land Degrad. Dev. 28 (7), 1891–1901.

Tebebu, T.Y., Steenhuis, T.S., Dagnew, D.C., Guzman, C.D., Bayabil, H.K., Zegeye, A.D., Collick, A.S., Langan, S., MacAlister, C., Langendoen, E.J., Yitaferu, B., 2015. Corrigendum: improving efficacy of landscape interventions in the (sub) humid Ethiopian Highlands by improved understanding of runoff processes. Front. Earth Sci. 3, 57.

Tech, T., 2011. Statistical Analysis for Monotonic Trends.

Tilahun, S.A., 2012. Observations and Modeling of Erosion from Spatially and Temporally Distributed Sources in the (Semi) Humid Ethiopian Highlands. Cornell University, Ithaca NY. PhD thesis.

Tilahun, S.A., Guzman, C.D., Zegeye, A.D., Ayana, E.K., Collick, A.S., Yitaferu, B., Steenhuis, T.S., 2014. Spatial and temporal patterns of soil erosion in the semi-humid Ethiopian Highlands: a case study of Debre Mawi watershed. In: Nile River Basin. Springer, Cham, pp. 149–163.

Tilahun, S.A., Guzman, C.D., Zegeye, A.D., Dagnew, D.C., Collick, A.S., Yitaferu, B., Steenhuis, T.S., 2015. Distributed discharge and sediment concentration predictions in the sub-humid Ethiopian Highlands: the Debre Mawi watershed. Hydrol. Process. 29 (7), 1817–1828.

Tilahun, S.A., Guzman, C.D., Zegeye, A.D., Engda, T.A., Collick, A.S., Rimmer, A., Steenhuis, T.S., 2013. An efficient semi-distributed hillslope erosion model for the subhumid Ethiopian Highlands. Hydrol. Earth Syst. Sci. 17 (3), 1051–1063.

Walling, D.E., 2006. Human impact on land–ocean sediment transfer by the world's rivers. Geomorphology 79 (3–4), 192–216.

Walling, D.E., 1974. Suspended sediment and solid yields from a small catchment prior to urbanization. Fluvial Process. Inst. Watershed. 6, 169–192.

Walter, M.F., Steenhuis, T.S., Haith, D.A., 1979. Nonpoint source pollution control by soil and water conservation practices. Trans. ASAE 22 (4), 834–840.

Warrick, R.A., 1980. Drought in the great plains: a case study of research on climate and society in the USA. IIASA Proceedings Series. In: Ausubel, J., Biswas, A.K. (Eds.), Climatic Constraints and Human Activities, vol. 10. Pergamon Press, New York, pp. 93–123.

Worqlul, A.W., Jeong, J., Dile, Y.T., Osorio, J., Schmitter, P., Gerik, T., Srinivasan, R., Clark, N., 2017. Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. Appl. Geogr. 85, 1–13.

Yimanie, T.A., Zaitchik, B.F., Simane, B., Ambelu, A., 2019. Changing patterns of tree cover in a tropical highland regions and implications for food, energy, and water resources. Front. Environ. Sci. 7, 1.

Zegeye, A.D., Langendoen, E.J., Guzman, C.D., Amare, S.D., Tilahun, S.A., Steenhuis, T. S., 2017. Gullies, a critical link in landscape soil loss: A case study in the subhumid highlands of Ethiopia. Land Degrad. Dev. 29 (4), 1222–1232. https://doi.org/10.1002/ldr.2875.

Zegeye, A.D., Langendoen, E.J., Guzman, C.D., Dagnew, D.C., Amare, S.D., Tilahun, S.A., Steenhuis, T.S., 2018. Gullies, a critical link in landscape soil loss: a case study in the subhumid Highlands of Ethiopia. Land Degrad. Dev. 29 (4), 1222–1232.

Zegeye, A.D., Langendoen, E.J., Stoof, C.R., Tilahun, S.A., Dagnew, D.C., Zimale, F.A., Guzman, C.D., Yitaferu, B., Steenhuis, T.S., 2016. Morphological dynamics of gully systems in the sub-humid Ethiopian Highlands: the Debre Mawi watershed. SOIL, 2 Soils 2, 443–458. https://doi.org/10.5194/soil-2-443-2016, 2016.

Zegeye, A.D., Damtew, S., Tilahun, S.A., Langendoen, E.J., Dagnew, D.C., Guzman, C.D., Tebebu, T.Y., Steenhuis, T.S., 2014. Gully development processes in the Ethiopian Highlands. In: Bantyirga, B., Mehari, M., Rao, V.S., Manocha, B.L., Singh, K.K., Geremew, S., Tadesse, E. (Eds.), 2nd International Conference on the Advancements of Science and Technology. Bahir Dar Institute of Technology, Bahir Dar Ethiopia, pp. 220–229.

Zimale, F.A., Tilahun, S.A., Tebebu, T.Y., Guzman, C.D., Hoang, L., Schneiderman, E.M., Langendoen, E.J., Steenhuis, T.S., 2017. Improving watershed management practices in humid regions. Hydrol. Process. 31, 3294–3301. https://doi.org/10.1002/hyp.11241.

Zimale, F.A., Moges, M.A., Alemu, M.L., Ayana, E.K., Demissie, S.S., Tilahun, S.A., Steenhuis, T.S., 2018. Budgeting suspended sediment fluxes in tropical monsoonal watersheds with limited data: the Lake Tana basin. J. Hydrol. Hydromechanics 66 (1), 65–78.